Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 85 (2014) 543 – 552

Procedia Engineering

www.elsevier.com/locate/procedia

Creative Construction Conference 2014, CC2014

Using LOD in structural cost estimation during building design stage: Pilot study

Jamin Wood[a], Kriengsak Panuwatwanich[a,*], Jeung-Hwan Doh[a]

[a]Griffith School of Engineering, Griffith University, Gold Coast campus, Queensland, 4222 Austalia

Abstract

This paper presents a pilot study attempting to harness the power of Building Information Modelling (BIM), coupled with Level of Development (LOD), for practicing structural engineers to have greater understanding of design decisions on cost, thereby giving greater control of economy. This study aimed to exploit the wealth of BIM built environment data in a framework, matching building material data with cost data, in the Microsoft Excel platform to allow for a raw design cost to be automatically determined. Level of Development (LOD) is a standard which allows for consistent comparisons between BIM models by ensuring each model covers a specified scope. There are multiple LOD's and by applying the framework at each of these, insight can be gained into the design cost over time as it is refined. To achieve the aim of the study, the tool was employed on five separate structures: two blockwork medium-rise buildings and three reinforced concrete high-rise buildings. Results indicate that similar structure types have similar design cost curves when data was standardised. By employing the process over further studies, the empirical curves will be refined with greater certainty, allowing for eventual use as benchmarks to assess economic performance of design solutions.

Peer-review under responsibility of the Diamond Congress Kft.

Keywords: building information model; building; cost estimation; design stage; level of development

1. Introduction

Despite being the largest sector in Australia, the Architectural, Engineering and Construction (AEC) industry has historically and persistently low levels of productivity. One of the recent advances within the AEC industry is the

* Corresponding author. Tel.:+617-5552-7357
E-mail address: k.panuwatwanich@griffith.edu.au

Peer-review under responsibility of the Diamond Congress Kft.
doi:10.1016/j.proeng.2014.10.582

development of Building Information Modelling (BIM), touted as an IT-induced paradigm shift for the sector. According to Succar [1], BIM represents a methodology to manage building design and project data in a digital format throughout the buildings' life-cycle. BIM is generally applied with the notion of decreased project costs, increased productivity and quality, and reduced project delivery time [2]. These expectations of BIM provide grounding for the need to conduct research into how this may economically benefit structural design.

BIM provides a mechanism to assess structural designs in terms of economics by utilising the latest, most up-to-date project information from all participants. By extracting relevant information from a model, this can be summarised in a form comprehensible by all industry across the board. Linking this with cost information can provide for a design cost estimate. It is possible to track the design cost as the structural solution is refined, and by doing so in many cases, provides a benchmark for design. Unfortunately BIM alone suffers from a lack of clarity in communicating structure definition for the correct uses as intended by the model author. The Level of Development (LOD) concept developed by the American Institute of Architects (AIA) addresses this issue with sufficient scope to allow for BIM to be used to track design cost estimation throughout all design stages. Since LOD is stringently defined in terms of what content is modelled at each stage, comparisons can be made between different structures. By standardising this information, design cost curves can be derived for different structure types. It is intended that these, with further development, will be able to act as benchmark curves to allow project management to assess the economic performance of a design compared to a typical structure of similar construction.

2. Theoretical Background

2.1. BIM in structural design

BIM promises to synchronise the design process, especially as a result of interoperability. Linking BIM with structural analysis software allows for a workflow based on concurrent structural documentation, design and analysis, using Electronic Data Interchange (EDI) [3]. For example a structural designer may create a physical model based on existing architectural plans, or model, and apply material definitions. The physical model is essentially a model and view of the structure exactly as it is to be built. The analytical model is automatically generated from the physical model to include all the necessary parameters for analysis such as support conditions, member end releases, offsets, section and material properties, as well as loads and load combinations. Load cases are then applied and the entire analytical model is sent to a structural analysis package. An engineer then updates the analytical model as required, which in doing so updates the physical model and alerts the designer. Code checking criteria are also available inside the mainstream commercial BIM authoring tools (e.g. Autodesk Revit) for most major world standards. Since code checks and documentation use the physical structural model, in traditional workflow the drafter must wait for the structural engineer to complete the analytical model analysis before proceeding. BIM automates this process, providing for a smoother workflow. Upon completion of analysis, design documentation is then updated to reflect the latest design, a process which is repeated for every iteration of the design process in a traditional workflow. This process fragmentation in terms of design documentation and structural analysis information is addressed by BIM which helps make the process smoother through automatic coordination.

2.2. Material quantity takeoff using BIM

BIM-based quantity takeoff for cost analysis is only worthwhile when used in conjunction with rigorous, up-to-date and location specific, material cost information. This information was used by Akbarnezhad et al. [4] to calculate a design cost by extracting quantities from the BIM database and multiplying by the defined unit price. Provisions for construction, demolition, assembly, disassembly, transportation and the like were estimated automatically from the size of work required multiplied by respective unit cost factors. A similar study was put forward by Fu et al. [5] who developed an IFC based life-cycle costing tool to evaluate design options. Due to automation, BIM offers great advantages over traditional cost estimating procedures, while exerting significantly less effort [6]. Nonetheless, literature on BIM-based material quantity takeoff is scarce, most likely due to underutilisation of the feature. This could also be due to the lack of knowledge sharing in private enterprise, which would deliver a considerable edge to anyone who masters the process [7].

2.3. Level of development (LOD)

LOD has the ability to resolve an issue which stems from BIM material quantity takeoff – at what point should the process be implemented? It acts as a standardisation which ensures the design cost is calculated at the correct time. A BIM model, by its very nature implies an exact quantity, whether it is intended to be or not. This is highlighted by the fact that in the BIM environment, elements may look identical regardless of whether a generic component is placed approximately or a specific component is placed precisely [8]. This is the reason the Level of Development (LOD) concept was introduced by The American Institute of Architects (AIA) in the document AIA E202 – 2008 [9]. LOD is useful to ensure the right amount of data is used in the cost estimation process and allow AEC practitioners to clearly articulate the content and reliability of a BIM model at various design and construction stages [8].

There are five LOD's in the BIM context which reflect five standardised models allowing for comparisons to be made with confidence. These are listed as follows [10]:

- LOD 100 is the initial concept estimate stage;
- LOD 200 is the schematic design stage;
- LOD 300 is the developed design stage;
- LOD 400 arises as the information in the model is revised to produce construction documentation, cumulating in LOD 500 which is a BIM model reflecting the 'as-built' structure.

Note that the aim of the study is to provide cost estimation at design stages, and so the 'as-built' structure is not as important, and not considered in this study.

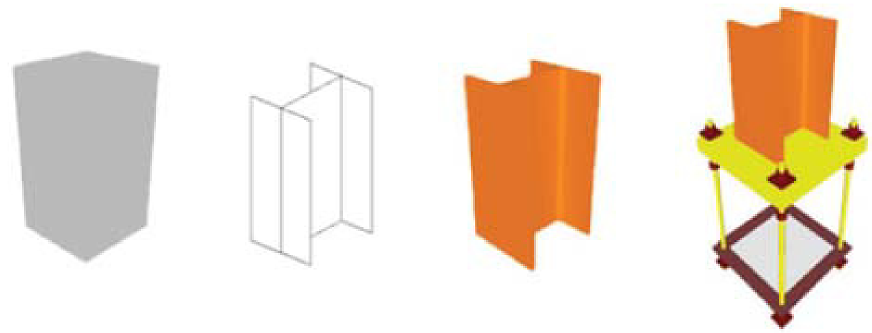
An important distinction should be explicitly made at this point with respect to the LOD definition. While LOD is used interchangeably to mean both Level of Development and Level of Detail by many professionals, the terms are in fact different. Level of detail is quite literally a measure of how much detail is included in a model element, whereas Level of Development is the level of thought that has been put into an element, or the degree to which users may rely on information [8]. A summary of the LOD requirements and authorised uses for cost estimating is provided in Table 1.

Table 1. Level of Development standard requirements and the corresponding use authorised for cost estimation [9]

LOD	Model content requirement	Authorised uses for cost estimating
100	Overall building massing indicative of area, height volume, location and orientation	Develop based on current area, volume or similar conceptual estimating techniques (eg. square meter of floor)
200	Generalised systems or assemblies with approximate quantities, size, shape, location, and orientation. Non-geometric information may be attached to elements	Develop cost estimates based on the approximate data provided and conceptual estimating techniques (eg. Volume and quantity of elements or type of system selected)
300	Specific assemblies accurate in terms of quantity, size, shape, location and orientation. Non-geometric information may be attached to elements	Develop cost estimates based on the specific data provided and conceptual estimating techniques
400	Specific assemblies that are accurate in terms of size, shape, quantity, and orientation with complete fabrication, assembly, and detailing information. Non-geometric information may also be attached to elements	Based on actual cost of specific elements at buyout

500	Constructed assemblies actual and accurate in terms of size, shape, location, quantity, and orientation. Non-geometric information may also be attached to elements	N/A

While the AIA documents set out the standard practices, they do not provide specific information on how to implement these standards. The *BIM Forum* (https://bimforum.org) has developed a LOD specification to address this. The specification contains tables of particular BIM model elements, each showing what particular requirements should be incorporated at each LOD. The requirements listed in this document and by the AIA have been used as the basis for defining the LOD requirements for the BIM models developed in this study [8]. A graphical representation of this information for a typical steel section is shown below.



LOD 100 – Conceptual mass | LOD 200 – Preliminary Universal Column (UC) steel section | LOD 300 – Detailed 150UC37.2 steel section | LOD 400 – Construction details, including connection information

Fig. 1. LOD progression of a steel column section [8]

3. Research Method

3.1. Overview

Framework development to utilise BIM in cost estimation of structural designs revolves around two key concepts – material information from a BIM model, and cost information from an external database (see Figure 2). Cost information includes provisions for material, labor, overheads, transport, and profit. The 2011 edition of *Rawlinsons Australian Construction Handbook* was used for this purpose, whereby a database was created for as many foreseeable commercial multi-storey building designs, using Brisbane, Australia as an arbitrary base location. Conversion factors are available in the guide for other locations [11]. To incorporate the LOD concept, there obviously had to be some variation in the cost database to reflect the different levels of development of a BIM model. Not only is there greater certainty in a design as it progresses from one LOD to the next, but there is also a greater amount of elements that should logically be defined.

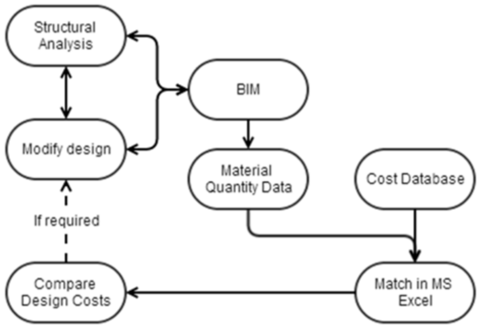


Fig. 2. Cost estimation framework

There are numerous alternatives to achieve material quantity takeoff from Autodesk Revit, the chosen BIM platform in this study. These include Autodesk Quantity Takeoff (QTO), COBie spreadsheets, third-party software, and procedures inside Autodesk Revit itself such as schedules and database links. COBie spreadsheets are mainly targeted towards facility management, however should be monitored into the future to assess whether they develop into an industry standard for material quantity takeoff under the context of this study. In order to simplify the framework and make it more accessible for users, it was prudent to ensure that only the basic Autodesk Revit software is required. By elimination, the only option was to use schedules from inside Revit, referred to henceforth as Material Take-Off (MTO). MTO allows extraction of the following information (Table 2) through schedules, used at each specified LOD.

Table 2. Revit schedule capabilities

Revit Schedule	Information extracted	Applicable to LOD
Mass floor schedule	Building Gross Floor Area	100
Multi-Category Takeoff	Number of different elements, and the respective total volumes and areas	200 & 300
Structural Framing Schedule	Framing lengths	200 & 300
Structural Column Schedule	Column lengths	200 & 300
Rebar Schedule	Reinforcement mass	400
Fabric Reinforcement Schedule	Fabric reinforcement mass	400
Generic Model Schedule (using post tension family as instructed in Wood [12])	Post tension mass	400
Structural Connection Schedule	Number of each connection type	400

In addition, Table 3 was derived to establish the LOD requirements of concrete and steel structures in the context of this study. Note that LOD 500 is not listed because it is not considered in this study.

Table 3. LOD specifications used in study

LOD	Concrete Structure	Steel Structure
100	Mass model to illustrate the conceptual building footprint	Mass model to illustrate the conceptual building footprint
200	Concrete type (traditional reinforced or prestressed) and approximate geometry, for example depth of elements	Type of steel system (standard frame, braced tube, and so forth) and approximate geometry.

300	Specific element modelling (sizes, locations and orientations) and concrete strengths. The following are *not* required to be modelled (however may be defined with notes): reinforcement, post-tension profiles and strand locations, penetrations for MEP services, finishes and so forth	Specific element modelling (sizes, locations and orientations) and material properties. The following are *not* required to be modelled (however may be defined with notes): connection details, finishes (painting, galvanising).
400	All reinforcement should be modelled, including post-tension detailing. Penetrations, surface finishes and camber should also be modelled	All connection details should be modelled including welds, coping of members, plates, bolts, washers, nuts and all assembly elements.

With ground work achieved into preparing cost and material information for comparison, a function or script is required to match cost and material information together. Basically it needs to read the BIM object descriptions, then look at cost object descriptions and select the best match. A best match is required as the nature of the databases mean the naming conventions are different. The platform to achieve this matching is inside Microsoft Excel – chosen for is universal acceptance and understanding throughout all industry. Several user-defined functions complete this stage of the algorithm as illustrated in Wood [12].

The general details of the material information, cost information and matching technique have now been introduced, and so it follows that the framework must then handle the information to yield a design cost. This is based on a very simple and fundamental equation:

$$Element\ cost = (Unit\ cost) \times (Element\ quantity) \quad (1)$$

Clearly there must be consistency of units for this equation to hold true. With the element cost derived, the process is completed for all elements in a BIM model, and then summed to yield at design cost for the LOD.

3.2. LOD cost estimation

LOD plays a standardisation role in the framework, however it also allows for useful analytical information to be gained, a direct result of the different BIM models which are developed at these predetermined stages over the temporal dimension. Applying the framework at each of these stages allows for cost information to be derived in the form of a curve varying with time.

In order to make comparisons between different design cost curves for different structures, some form of data standardisation is required. It was put forward by the authors that for structures of similar structural system, material, and construction type, the design cost curves are the same shape, albeit out by a certain factor to account for the differing scopes of each building. This factor can be negated to allow for comparisons by creating relative figures calculated using the below equation:

$$Relative\ cost = \frac{Cost\ at\ specific\ LOD}{LOD\ 100\ cost} \quad (2)$$

In this context, LOD 100 can be thought of as a measure of the building scope as it is proportional to gross floor area. It is clear that relative cost is the dependent variable in design cost; however the independent variable requires discussion. LOD gives no indication of the effort required to create each model, and that is important in the narrative over a temporal dimension. It is also put forward, and verified in later discussion, that as LOD increases, influence on the design cost decreases because design decisions which most heavily influence design cost occur in the early stages of the LOD process [13]. For example, the structural system and structural material are generally defined by the LOD 200 stage to reflect the AIA requirements. While different alternatives may be investigated, these are done in separate analysis and so yield separate DCM curves. It is for these reasons that design cost is most heavily influenced in early design stages, and so it is not reasonable to plot a DCM curve against LOD. The curves are plotted against a new variable, relative effort, which is defined in a similar manner to relative cost:

$$Relative\ effort = \frac{Cumulative\ effort\ to\ specific\ LOD}{LOD\ 400\ effort} \tag{3}$$

Using relative effort as the independent variable ensures the curve is more asymptotic in nature, and so provides a better idea of where the design cost is likely to head, and how much effort is required to refine it to the desired level, than if LOD is used. Using LOD yields a plot which is more linear for the reasons specified above. LOD 400 effort is used because it is the maximum effort expended over the course of the analysis, and so the relative value will always be less then unity. By establishing the effort to create a BIM model, this information can be used to allow for empirical relationships to be derived for final design cost, even when using data from the initial conceptual stage.

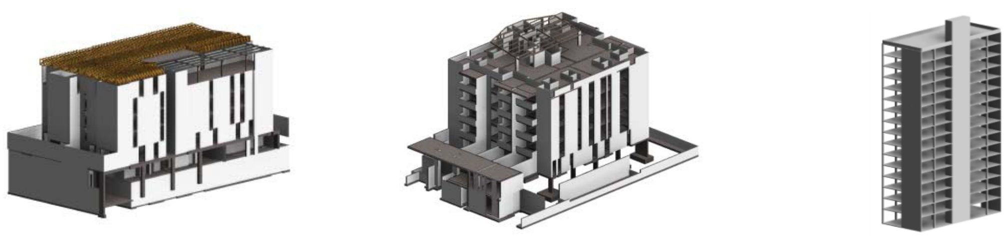
One question that may have arisen at this point is, wouldn't user experience have an influence on the design cost curve? It is shown by Wood [12] that the influence effort has on the LOD 400 estimate from the design cost curve is often one order of magnitude less than the associated change in effort. In other words, if the effort changes by say 100%, the effect on the LOD 400 estimate would be ~10%. Furthermore, because the process uses relative effort, and it is relatively safe to assume that the ratio of time spent for each LOD would be similar between users, the overall impact is negligible for estimating purposes.

The design cost management process is envisaged to allow for empirical graphs to be derived for specific structure types providing a realistic forecast, with upper and lower bounds, for a design cost at construction, using early conceptual information. Obviously to yield these types of empirical curves, the framework would need to be employed over many different case studies of each type. Ultimately, it is expected that these curves would form a benchmark for future structures. This would give engineers and management the best chance to identify poor economic performance of a structure, and make subsequent improvements.

4. Results and Discussion

The framework was applied to five cases as shown in Figure 3. Cases I and II are very similar in terms of both being blockwork and reinforced concrete structures, and also in terms of scope. They should therefore produce relatively similar curves. A similar notion exists for Cases III to V structures.

Figure 4 compares various curves of the relationship between relative cost and effort for all the five investigated cases. It should be noted that the blockwork structures (Cases I and II) use a logarithmic regression analysis, while the 16 storey office structures (Cases III to V) use a power regression analysis. This reflects the aspect that for different types of structures, the design cost curve can have a different shape, and so a different regression analysis function is required to best fit the data. Applying this process to many other structures of the same types would verify whether these choices are truly appropriate for the wider, general empirical curves as the benchmark for economic evaluation of designs. This decision is governed by the R^2 values.



Case I: Five storey reinforced concrete /blockwork office.

Case II: Six storey reinforced concrete/ blockwork apartments.

Cases III, IV and V: Sixteen storey reinforced concrete office buildings with 6m, 8m and 10m shear wall lengths, respecitvely.

Fig. 3. Case studies

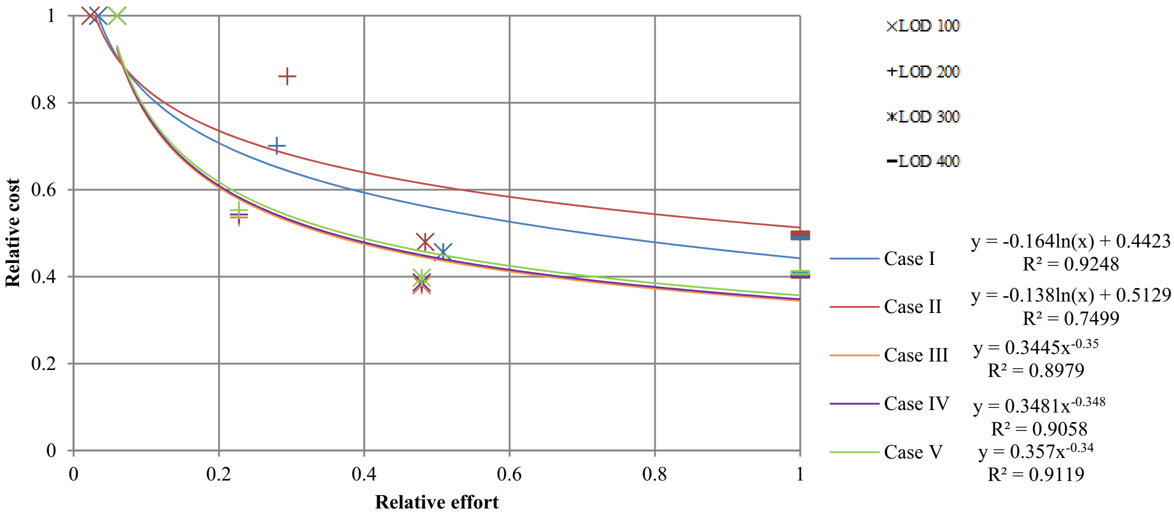


Fig. 4. Design cost curves of the five investigated structures

The two functions derived for the Case I and II structures predict LOD 400 relative costs of 0.44, and 0.51 respectively. If an average for this structure type is taken, the LOD 400 relative cost prediction would be 0.475±0.035. This is an illustrative range, and confidence would increase as more structures of a similar type are put together under analysis.

While the design alternatives for Cases III to V (16 storey structures) do have changes in relative cost, it is far less than those for different structure types. It is worthy to analyse that the apparent confidence for the 16 storey structure is greater than for the blockwork structures, when predicting LOD 400 using the modelled equations. This is perhaps best explained as the office structures are predominantly similar. The aim of this analysis is not to expect the curves to be identical, however they should be similar enough that an average of many examples of the structure type reveals a different curve than for another structure type. A further explanation could be because the model for Case II is a relatively poor fit ($R^2 = 0.75$).

Discussion is warranted to the shape of the design cost curves. For example, note the asymptotic behavior of the curves. The downward curvature is best attributed to the increasing definition of a structure. At LOD 100 it may be known to be an office building. This could be of many different materials and construction types. The LOD 200 cost has an idea of this information, and it would be expected that the designer would choose a system which is cheaper than the average of all types of systems, which is why the curve goes down. Similarly for other LOD's, increasing the project definition incorporates design decisions, which if following good economic performance will be chosen such that they are cheaper than the average of all possible solutions incorporated into the previous LOD cost.

5. Limitations and Future Work

It must be stressed the figures presented in the preceding section are only for the structural system modelled. This in no way reflects the cost of the building to a client, and should be used only as a tool to evaluate the effectiveness of a structural engineer to minimise costs of only the structural system. The calculation was also based on the material price data for the city of Brisbane, Australia. As such, the output design value should be seen as only an indicative value for the structural system – framework does not attempt, nor should it, to quantify, or cost, non-structural elements. It is envisaged that firms will in fact have accrued their own cost databases in their experience, and so the limitation to Brisbane-based projects may not be overly consequential. Furthermore, conversion factors between different locations in Australia are also provided in Rawlinsons Australian Construction Handbook, and this information could be utilised to apply the framework in different locations as required.

The real power of the framework comes to fruition when BIM is fully implemented into AEC projects. This is because, the BIM model would be constantly revised and updated by all professionals, and so containing the latest information known on the project. The model therefore exists, and cost estimation is almost instantaneous from that point. Essentially the framework is a small additional process that can be added to the BIM workflow, utilising BIM data, to produce timely cost estimates for structural designs. It would be worthy to implement the framework into a real-time project to analyse what time saving benefit the framework offers over traditional economic evaluation procedures.

While the framework was developed solely to satisfy the need for an enhanced costing mechanism of structural designs, in the changing global climate where sustainable design is becoming a critical element of projects, the framework can be further applied to environmental impact assessment. The environmental footprint of a building can be quantified in terms of embodied energy and carbon, and if a database can be made to quantify each of these with respect to each structural element, a carbon database can be constructed, analogous to the cost database. This information would be invaluable in accounting for, and comparing sustainable designs. It would also assist in providing to a client what effect prices on carbon, such as an Emissions Trading Scheme, would have as a result of decisions by the structural engineer.

The eventual goal of the developed framework is to provide an automatic economic evaluation and optimisation procedure for structural design. It is envisaged the developed framework could lend weight to structural optimisation procedures, especially given the holistic building view BIM offers.

6. Conclusion

This study developed a framework to utilise the power of BIM in performing cost estimation of structural design options. In practical implementation this will allow for an enhanced interactive design process between all stakeholder parties, resulting in more efficient and economic solutions. The general approach taken by the framework was to extract material information from BIM, and then provide an algorithm to fuzzy match BIM objects with cost data. Multiplying both data sets together, after assessing for correct units, allowed for a total design cost to be made. By using the LOD concept, economic information could be determined over the temporal dimension. While only a few structures were tested in this study, it is envisaged that empirical relations will be derived for certain structure types. This will give framework users a benchmark to assess the economic performance of a structural design. Furthermore it will give an indication of where the design cost is likely to head, and how much the design needs to be refined to get there. Further testing of the framework is required to ensure the approach is valid in a greater selection of design alternatives. With future industry collaboration and development, it is envisaged the framework will have a role to play in the design process to ensure design solutions stand up to economic scrutiny.

References

[1] Succar, B. (2009). 'Building Information Modelling framework: A research and delivery foundation for industry stakeholers', Automation in Construction, 138, 853-63.
[2] Azhar, S. (2011). 'Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry', Leadership and Mangement in Engineering, 11, 241-52.
[3] Ikerd, W.F. (2007). BIM and the Structural Engineer: Why you need to pay attention, Intertech Design: Department of Advanced Building Design.
[4] Akbarnezhad, A., Ong, K.C.G., Chandra, L.R. & Lin, Z. (2012). 'Economic and Environmental Assessment of Deconstrucion Strategies Using Building Information Modeling', paper presented to Construction Research Congress.

[5] Fu, C., Kaya, S., Kagioglou, M. & Aouad, G. (2007). 'The development of an IFC-based lifecycle costing prototype tool for building construction and maintenance', Construction Innovation, 7, 85-98.
[6] Pishdad-Bozorgi, P., Moghaddam, E. H. & Karasulu, Y. (2013). 'Advancing Target Price and Target Value Design Process in IPD Using BIM and Risk-Sharing Approaches', paper presented to 49th ASC Annual Internation Conference Proceedings.
[7] Monteiro, A. & Martins, J.P. (2013). 'A survey on modeling guidelines for quantity takeoff-oriented BIM-based design', Automation in Construction, 35, 238-253
[8] Reinhardt, J., Bedrick, J., Ikerd, W., Vandezande, J., Dellaria, R., Karakas, M., Merrifield, D., Cichonski, W., Filkins, B., Francis, D. & Lawson, A. (2013). BIM Forum: Model Development Specification.
[9] Bedrick, J. (2008). Organizing the Development of a Building Information Model, The American Institute of Architects.
[10] Smith, P. (2013). 'BIM & Project Cost Management - Implementation Issues & Creative Solutions', paper presented at the Creative Construction Conference, Budapest, Hungary, July 6-9, 2013.
[11] Rawlinsons Quantity Surveyors and Construction Cost Consultants (2011). Rawlinsons Australian Construction Handbook 2011, 29th edn, Rawlinsons Publishing, Perth, WA, Australia.
[12] Wood, J. (2013). 'An Application of Building Information Modelling in an Economic Evaluation of Structural Design Options', Undergraduate Thesis, Griffith University, Australia.
[13] Ali, N. B. H., Sellami, M., Cutting-Decelle, A. F. & Mangin, J. C. (2009). 'Multi-stage Production Cost Optimization of Semi-rigid Steel Frames Using Genetic Algorithms', Engineering Structures, 31, 2766-78.